
# *LAND: Precision Landing and Hazard Avoidance*
# NASA Space Technology Mission Directorate
# August 2022

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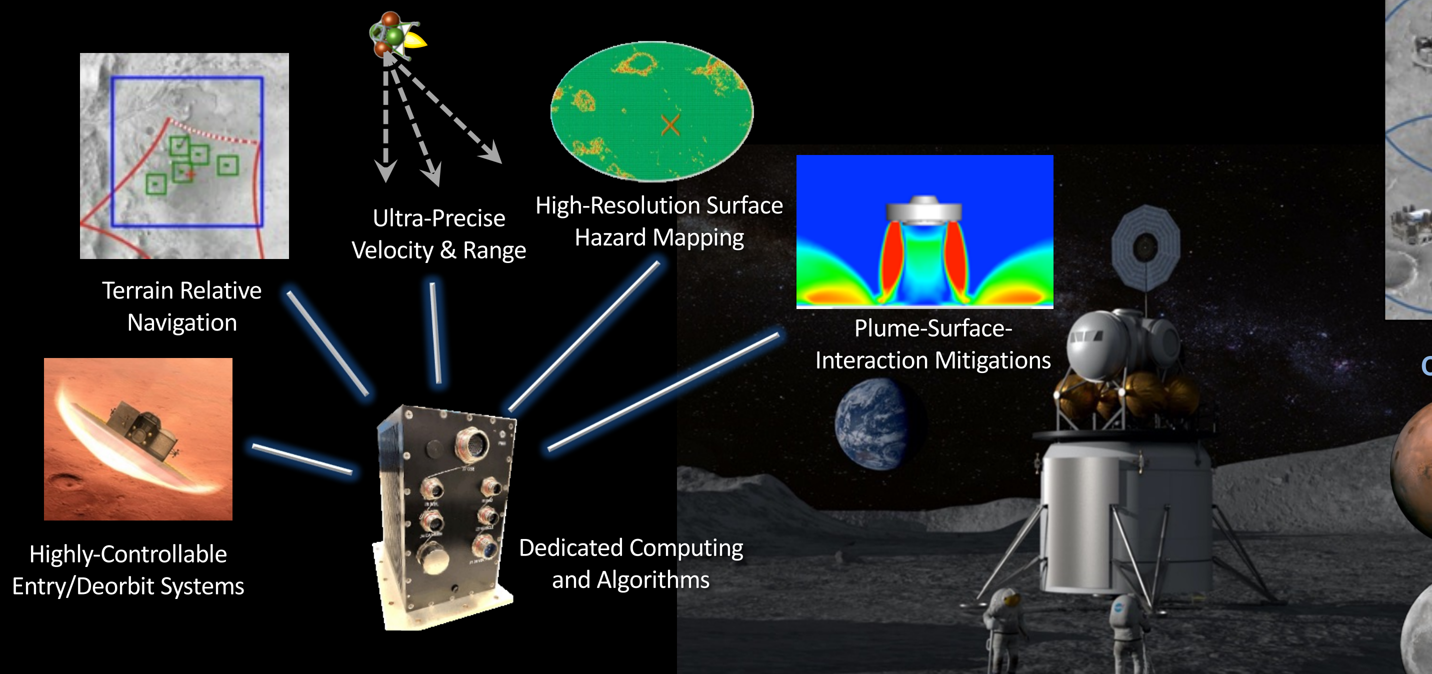
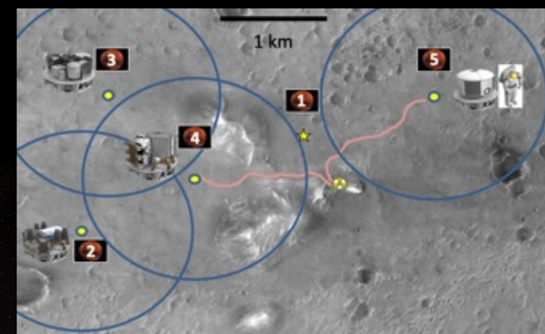
# LAND: Technologies to Precisely Land Payloads and Avoid Landing Hazards

*Developing entry, descent and landing technology to enhance and enable small spacecraft to Flagship-class missions across the solar system*




**Aggregated and Sustainable Sites on the Moon and Mars**




**Capabilities evolvable for many solar-system destinations**

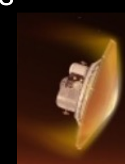
<u>Enable</u> anytime landings in treacherous terrains and independent of lighting
<u>Reduce the risk</u> of the landing for human and robotic missions to many destinations
<u>Reduce operations time</u> for a rover or human to reach an interesting site
<u>Aggregate resources</u> in one surface region for missions requiring multiple landings

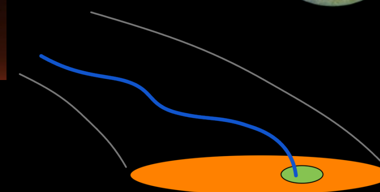
# Landing Precision: Description of Envisioned Future

## Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

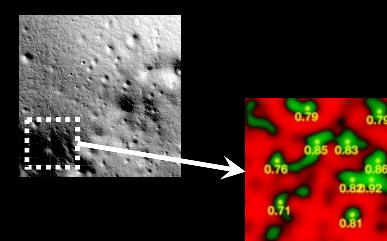
**EDL: Entry, Descent and Landing** (solar bodies with atmospheres) **DDL: Deorbit, Descent and Landing** (airless solar bodies)
**PL&HA: Precision Landing & Hazard Avoidance** (general term for precise safe landing capabilities)

- **What are some of the challenges?**
  - Precise and safe landing is not yet possible away from Earth
  - Human & robotic PL&HA differs – **no one-size-fits-all** for all missions but capabilities are evolvable
  - Human-class missions currently target 50-100m precision, whereas some robotic-class missions target 10-50m precision
  - Anytime landing requires functionality independent of surface lighting conditions



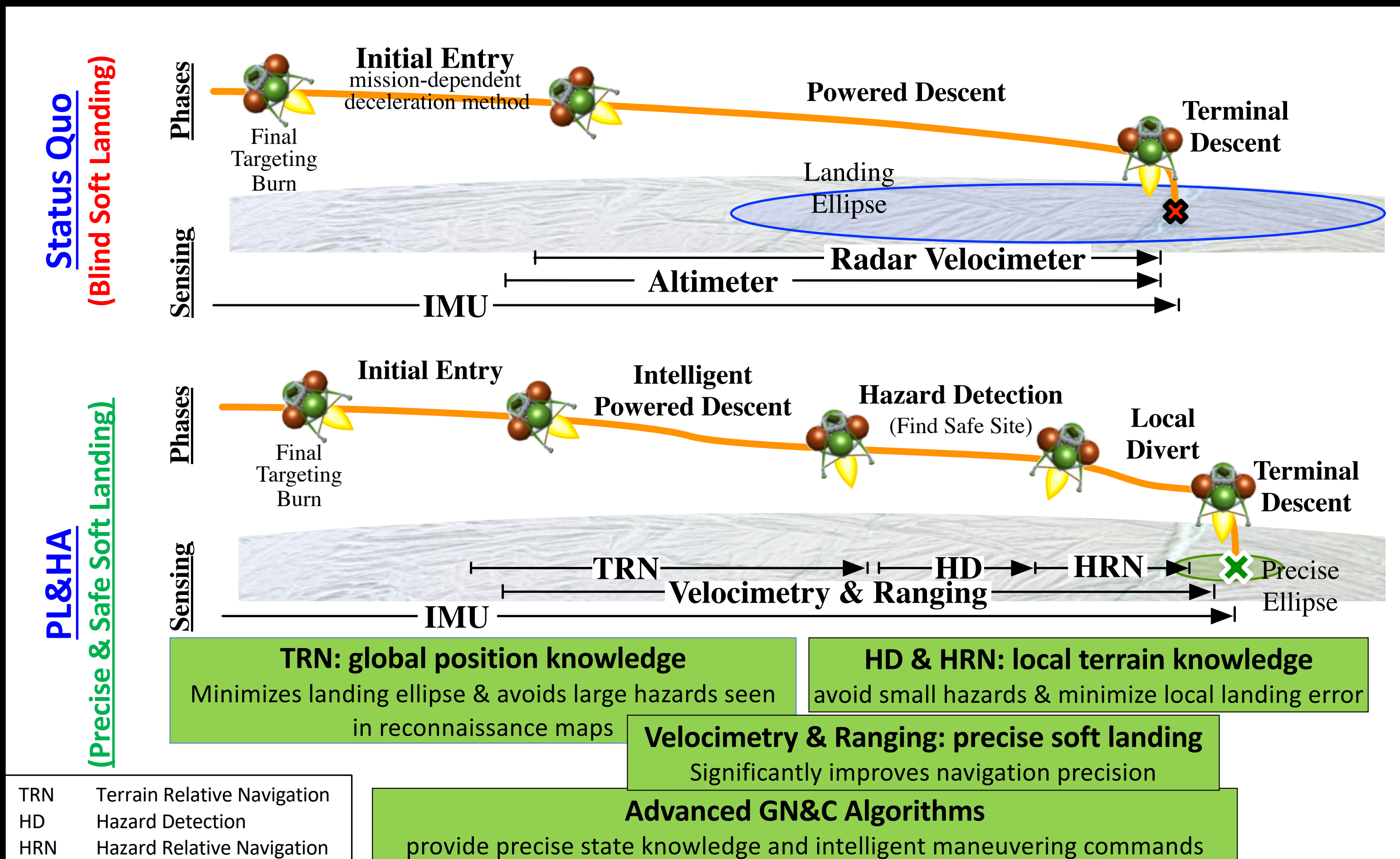


- **Description of Capability targets**
  - Highly-controllable EDL/DDL systems (hardware and algorithms) increase entry & descent maneuverability to facilitate fuel-efficiency and significant landing-ellipse minimization
  - Terrain relative navigation (TRN) facilitates propulsive/aero maneuvers to minimize landing ellipses and avoid large surface hazards identified in reconnaissance maps – global navigation without GPS
  - Precise velocity/range sensing facilitates soft landing and improves EDL/DDL navigation precision (current sensors are high size/mass/power, plus have high component/system-integration costs)
  - High-resolution terrain mapping during descent and landing facilitates hazard detection (HD) and avoidance of surface features not identifiable within reconnaissance maps – can also improve TRN maps in real time
  - Plume-Surface Interaction (PSI) mitigations facilitate improved landing sensing for soft, precise touchdown and minimize debris risks to the lander and other aggregated surface assets
  - Dedicated PL&HA computing minimizes processing-overload risks to primary flight computer during the critical EDL/DDL phase



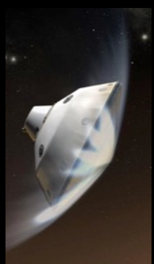
# Landing Precision: Status Quo Vs. PL&HA

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

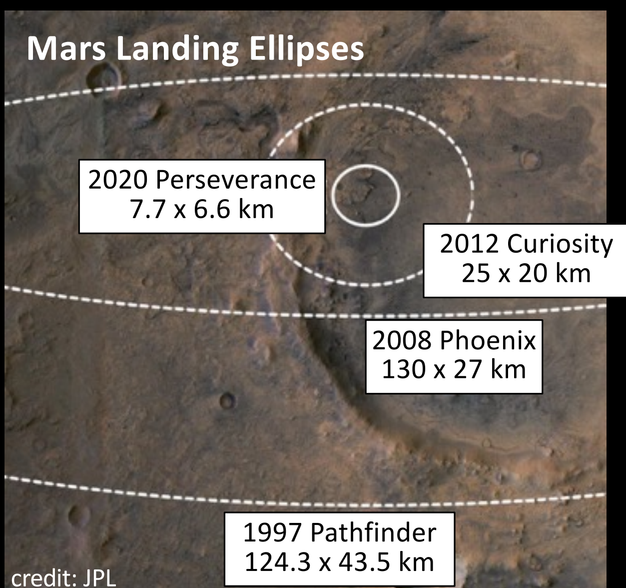


# Landing Precision: State of the Art (SOA)

## Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

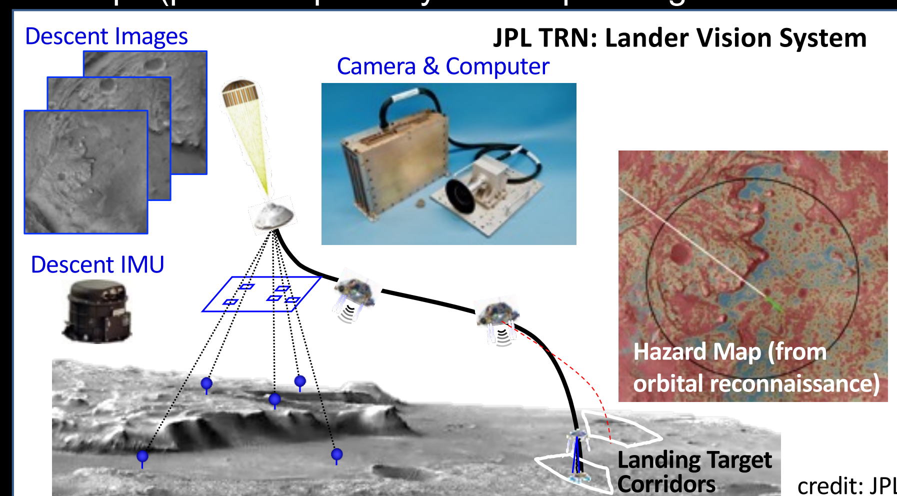


credits: JPL




credit: JPL

- Mars 2020 Mission successfully landed the Perseverance rover within a 7.7 x 6.6 km landing ellipse on February 18, 2021
- EDL system: Viking-style entry body, parachute-deployment range trigger, Apollo-based entry guidance (bank-angle reversal maneuvers), camera-based TRN (JPL Lander Vision System), and JPL Doppler radar (velocity and range)
- JPL TRN fuses camera images and IMU data for precise position localization relative to a reconnaissance map → enabled landing at a location identified as safe within reconnaissance maps (passive optical system requires lighted terrain on descent)



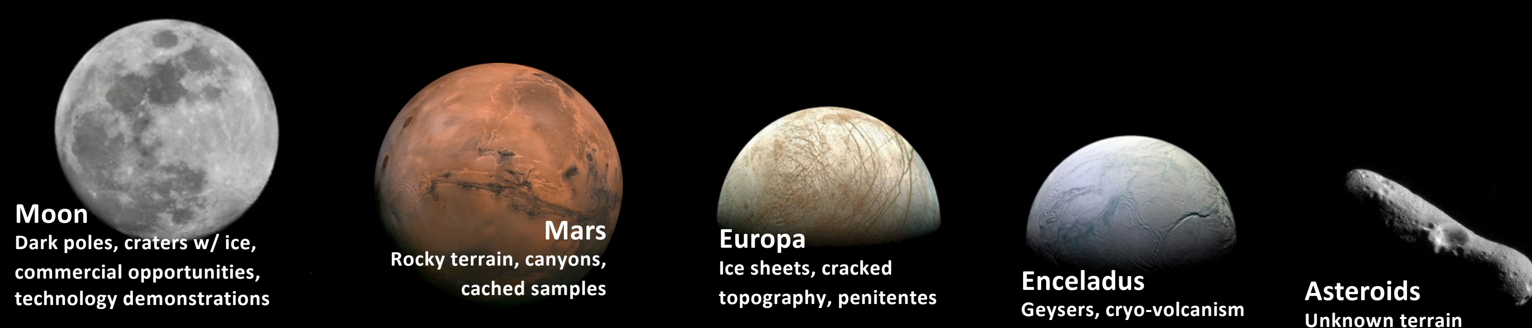

credit: JPL

Note on TRN SOA: multiple commercial, passive-optical TRN systems are in development with planned demos onboard two different 2022 robotic lunar landers

# Landing Precision: Development Strategy

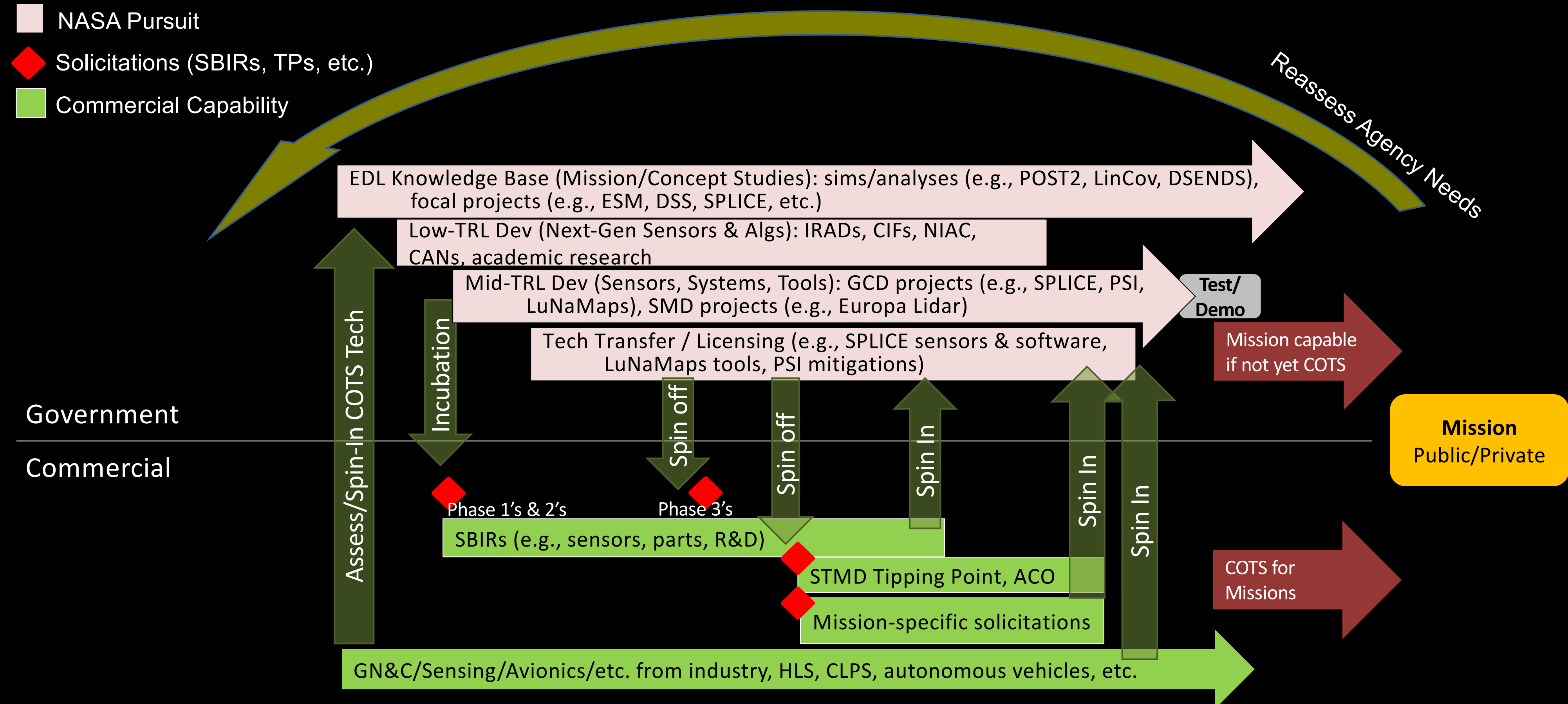
Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

- **Overarching Goal**
  - Develop, infuse, and commercialize technologies applicable to robotic and human landers that become part of the future suite of off-the-shelf GN&C (Guidance/Navigation/Control) capabilities for precise safe landing
- **Overview of Approach**
  - Sustain an EDL/DDL knowledge base and simulation to capture near-term and future human and robotic mission needs and the evolving commercial and government PL&HA capabilities
  - Prioritize development and infusion of cross-cutting EDL/DDL systems, sensors, avionics, and algorithms applicable to human and robotic missions
  - Leverage multiple test paradigms (lab, flight, suborbital, space) to accelerate TRL advancement and infusion
  - Pursue technology transfer, public-private partnerships, commercial spin-offs and spin-ins to promote closure of EDL/DDL capability gaps and the transition-into/leveraging-of commercial off-the-shelf (COTS) solutions



# Landing Precision: Strategy Visualization with Focal Approaches

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

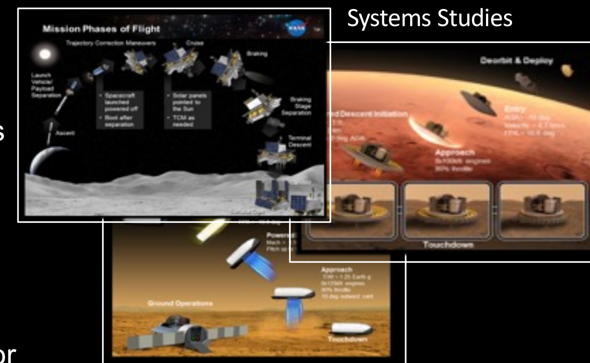


# Landing Precision: Approach to Develop the Capabilities

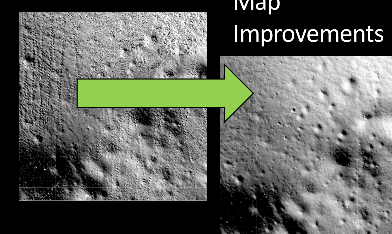
## Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

**Leverage focal agency projects, solicitations and partnerships to**

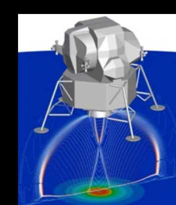
- **Evaluate highly-controllable EDL/DDL systems for future implementation**
  - study landing-precision improvements with novel aerodynamic bodies, new control architectures (e.g., dual-axis, direct-force) and GN&C advances
  - *closely coupled to separate EDL strategy package on "20t" landing capability*
- **Develop PL&HA hardware for anytime landing: TRN, HD, Velocimetry**
  - within NASA, initially pursue lidar development and commercialization to provide
    - active terrain sensing to enable TRN and HD during descent/landing over dark, shadowed, or illuminated surfaces
    - establish a baseline capability upon which to build future PL&HA approaches
  - solicit new sensor capabilities to facilitate technology transfer of NASA investments and to spin in industry advancements (e.g., advancements in radar, lidar, etc.)
  - following baseline approach, pursue future multi-function sensors, multi-capability systems based on lidar, radar or other active-sensing paradigms
  - pursue dedicated PL&HA computers for sensor fusion and algorithms processing in parallel with advancements in high performance spaceflight computing
- **Enable algorithms & processes supporting precise navigation & safe landing**
  - PSI modeling and validation via instrumentation to develop landing-system mitigations during terminal descent and touchdown
  - mapping tools/processes to improve TRN maps, surface ops, & mission planning
  - hazard detection and advanced guidance algorithms for landing-site identification and efficient descent/divert maneuvering



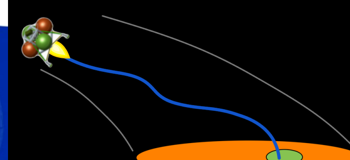

Systems Studies



Map Improvements



Plume Surface Interactions



Advanced PL&HA Algorithms

# Landing Precision: Approach to Mature & Transition the Capabilities

## Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

- Leverage multiple test and validation paradigms to develop, mature, and infuse capabilities

Concept → Capability

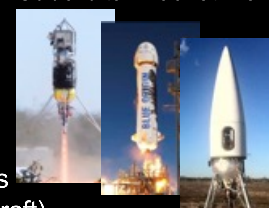
Computer Simulations

Lab Component Testing

Lab Dynamic System Testing

Aerial Vehicles and Field Tests
(drone, helicopter, fixed-wing aircraft)

Suborbital Rocket Demos

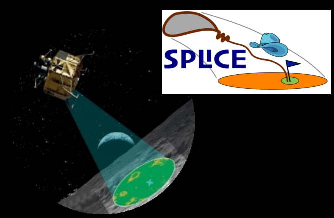


Lunar Demo

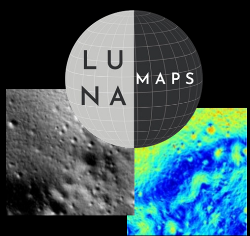
- Incubate public/private partnerships and technology commercialization/dissemination for TRL maturation and to maximize infusion/availability to government and commercial spaceflight missions
  - **Academic partnerships** (cooperative agreements, ECF/ESI, NSTGRO) continue to foster new innovations and incubate low-TRL concepts, plus mature the next generation of technologists and engineers
  - **SBIR/STTR solicitations** have been and will continue to develop PL&HA component supply chains and commercial solutions for current and next-generation sensors, including incubate and mature new low-TRL innovations
  - **Tipping Point solicitations** have promoted and will continue PL&HA commercialization and infusion
    - 2018 Tipping Point has promoted multiple commercial TRN implementations
    - 2020 Tipping Point is developing a next-generation suborbital capability for closed-loop GN&C/PL&HA testing
    - Discussing future solicitations for commercial Hazard Detection and integrated PL&HA systems
  - **Flight Opportunities 2022 Nighttime Precision Landing Challenge** will help promote commercial development of terrain mapping sensors for hazard detection – targeting general field of active sensors (lidar, radar, IR, etc.)
  - Open **NASA/industry workshops** are promoting ideas incubation for public-private partnerships and infusion
    - 2021 Lunar Mapping Workshop discussed mapping tools/processes, capabilities, and needs

# Landing Precision: NASA Projects Implementing the Approach

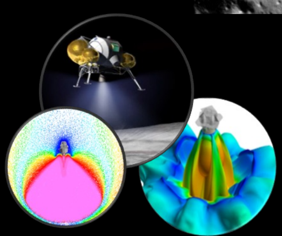
## Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards



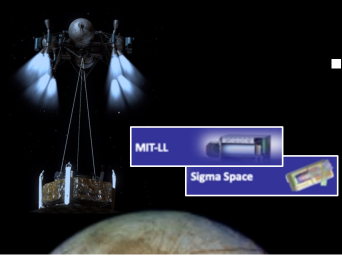

- **STMD/GCD SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution) Project**
  - Developing and field testing lidar for active terrain sensing during descent/landing over dark, shadowed, or illuminated surfaces
  - Implementing dedicated computing for sensor fusion and advanced algorithms processing in parallel with advancements in the NASA High Performance Spaceflight Computing (HPSC) initiative
  - Commercializing technologies: Phase 3 SBIR for NDL commercialization, flight software going into NASA Software Release System, partnering with CLPS/HLS companies on TRN dev and HD infusion/commercialization




- **STMD/GCD LuNaMaps (Lunar Navigation Maps) Project**
  - Developing mapping tools and processes to provide a capability critical to future lunar missions with feedforward to Mars and beyond (Open NASA/industry workshop occurred in 2021 to discuss tools/processes/needs)
  - Will generate navigation-quality lunar maps from orbital reconnaissance imagery for onboard uses
  - Will enhance maps with analog field data & synthetic surface features for ground-based algorithms assessments



- **STMD/GCD PSI (Plume Surface Interaction) Project**
  - Implementing simulation models and tools to predict PSI environments and enable smart design and risk analysis of EDL architectures
  - Developing instrumentation for ground testing (at relevant scales), collecting flight data, predicting PSI effects, and validating models → goal is to enable future PSI mitigation strategies




- **SMD** Europa Lander Concept: **ILS (Intelligent Lander System)**
  - Developing integrated TRN, Hazard Detection & Velocimetry capabilities for the unique environment of Europa
  - Technologies likely have broader mission applicability beyond Europa
  - Lidar-specific investments have potential for TRN and HD applications in other missions

# Landing Precision: Transition Status of NASA Investments (SPLICE)

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

**STMD/GCD SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution) Project** – Developing and Commercializing multiple sensors, algorithms, and a computing architecture for a broadly-applicable PL&HA baseline

SPLICE

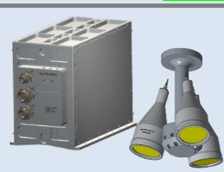
**(Commercialization/Licensing Statuses are Highlighted)**

## Sensors/Scanners

**Passive TRN**
**(Imaging & Inertial)**

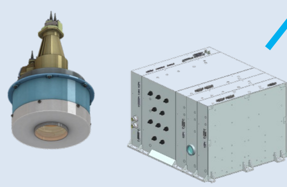
**Camera + IMU (both COTS)**

**Ultra-Precise Velocity & Range**



**Doppler Lidar**
**(Transitioning to COTS – Phase 3 SBIR)**

**Surface Hazard Imaging**
**(Map Generation)**



**Scan-Array Lidar**
**(Early licensing/infusion discussions)**

## Dedicated Computing

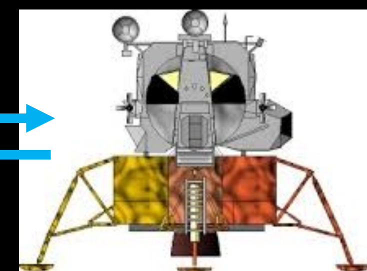
Precise EDL Navigation
PL&HA Guidance
Safe Site

Pre-EDL Navigation
Master Clock

**Descent & Landing Computer**
**(Early component licensing discussions)**

**Software Functions**
**(Licensable or Listable in NASA SW Catalog)**
TRN: Image Processing and Map Comparisons
Hazard Detection (Safe Site ID)
PL&HA Guidance
PL&HA Navigation

**Architecture**
SpaceVPX Architecture (Industry Standard)
HPSC-Surrogate (COTS + rad-tolerance provisions)
and Kintex FPGA (COTS) for I/O & co-processing

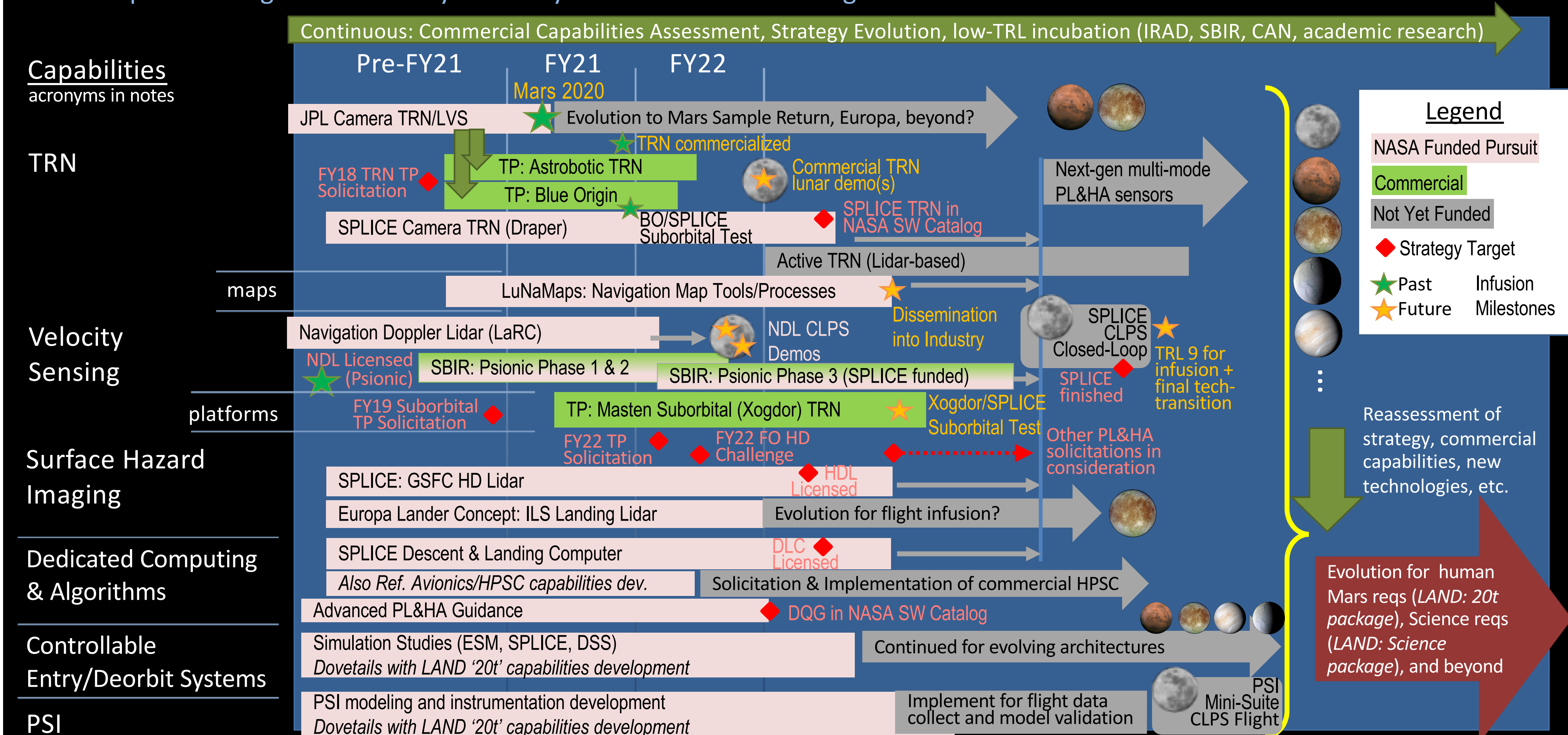


**Lander & Primary Computer**

**EDL Functions**
Vehicle Control
Non-PL&HA Guidance & Nav

# Landing Precision: Development, Evolution & Infusion Roadmap

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards



# Landing Precision: Highest-Priority Technology Gaps & the Closure Path

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

**Current project investments are poised to address the highest-priority gaps with safe and precise landing**

Current Investment (on closure path) | Current Investment (follow through) | Unfunded (Future Ask)

**LuNaMaps Project**

- **Gap: High-Resolution, Continuous Lunar Maps for Precise Landing**

**PSI Project**

- **Gap: Validated Prediction of Plume Surface Interaction (PSI) for Vehicles Landing on the Moon**
- **Gap: Flight Instrumentation to Acquire Plume Surface Interaction Performance Data**

**SPLICE Project**

- **Gap: Navigation and guidance technologies that provide precise knowledge and maneuver planning for Lunar missions**
- **Gap: Precision Landing and Hazard Avoidance Test Platform** (on closure path with Masten Tipping Point award for Xogdor platform development)
- **Gap: Dedicated high-performance computing for precise landing and hazard avoidance algorithms and sensor fusion** (tied to Avionics Gap for HPSC – High Performance Spaceflight Computing)
- **Gap: Real-time mapping technologies for active terrain relative navigation (TRN) and hazard detection and avoidance during lunar descent toward landing** (active TRN is increasing in priority for lunar South Pole landings)

# Landing Precision: Logical Next-Steps

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

Current Investment | Maintain | Future Need

**Summary of current approach**

- SPLICE: developing sensors, computing and software for a baseline integrated capability for precise and safe landing
- LuNaMaps: developing and disseminating lunar mapping tools/processes for use by government and industry with lunar landing
- Europa Lander Concept Study: developing EDL technologies for the unique environment of Europa with potential for broader infusion
- Modeling and Architecture Studies: high-fidelity EDL simulations are continuing mission concept studies to evaluate highly-controllable EDL systems, model PSI, and assess PL&HA technologies that enable the closure of EDL gaps and the strategy evolution
- Commercialization: solicitations for public-private partnerships, SBIRs, Tipping Points, etc. are accelerating technology commercialization (spin off and spin in) plus infusion into CLPS missions and non-space applications (consider incentivizing certain EDL/PL&HA technologies for various mission classes)

**What are the next steps?**

- Maintain concept studies, low-TRL investments, EDL-focused SBIR solicitations, STRG/academic awards, public-private partnerships, and commercialization to identify new technologies and evolve the development strategy
- Conduct planned demonstration tests to validate models, raise TRL, and mitigate infusion risks for EDL technologies
  - Conduct testing and then disseminate PSI-mitigation approaches for landing systems
  - Conduct a lunar demonstration of the SPLICE technologies being actively used (in closed loop) within a landing system
- Continue development toward future generations of EDL and Avionics Technologies
  - HPSC: continue development & commercialize → radiation-hard, multicore processing is critical to future envisioned missions
  - Europa Lidar: monitor advancement of systems for commercialization and broader-infusion prospects
  - Active TRN: develop lidar-based TRN for anytime, anywhere global access (e.g., EDL/DDL for dark/shadowed lunar regions)
  - Pursue multi-mode EDL/PL&HA sensors that further advance and miniaturize integrated capabilities

# Landing Precision: Summary

Develop Technologies to Land Payloads Within 50 m Accuracy and Avoid Landing Hazards

- **Strategy**
  - Develop safe and precise landing capabilities that increase surface accessibility for anytime and anywhere global access to locations that pose significant landing risk to missions
- **Goal**
  - Infuse and commercialize technologies to become part of the future suite of COTS (Commercial Off-The-Shelf) GN&C capabilities for human and robotic landing missions
- **Approach**
  - Prioritize development of cross-cutting systems, sensors, avionics, and algorithms
  - Sustain EDL knowledge base and simulation to capture and assess human and robotic mission needs
  - Implement via NASA centers, academic partnerships, solicitations, public-private partnerships, etc.
  - Leverage the NASA technology transfer process, publishing, licensing, etc. to transition technologies to COTS

# Acronyms for Precision Landing Technologies

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

- CAN: Cooperative Agreement Notice
- CLPS: Commercial Lunar Payload Services
- DDL: Deorbit, Descent and Landing
- DLC: Descent and Landing Computer
- DSS: Descent Systems Study (project)
- DQG: Dual Quaternion Guidance
- ECF: Early Career Faculty
- EDL: Entry, Descent and Landing
- ESI: Early Stage Innovation
- ESM: Entry Systems Modeling (project)
- HD: Hazard Detection
- HDL: Hazard Detection Lidar
- HPSC: High Performance Spaceflight Computing
- IRAD: Internal Research and Development
- LVS: Lander Vision System
- NDL: Navigation Doppler Lidar
- NSTGRO: NASA Space Technology Graduate Research Opportunity
- PL&HA: Precision Landing and Hazard Avoidance
- PSI: Plume-Surface Interaction
- SBIR: Small Business Innovative Research
- SW: Software
- TP: Tipping Point (commercial partnership projects)
- TRN: Terrain Relative Navigation